ADE000115

Cryogenically-Cooled Microwave Acoustic Delay Devices

RICHARD GURNEY

Advanced Techniques Branch
Tactical Electronics Warfare Division

January 1978

DDC

RECEIVED

MAR 1 1978

B

NAVAL RESEARCH LABORATORY
Washington, D.C.

ERRATA

NRL Memorandum Report 3620

Page 10, Reference #4, second line, SU-18, should read SU-19

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS
BEFORE COMPLETING FORM

1. REPORT NUMBER	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
NRL Memorandum Report 3620		

4. TITLE (and Subtitle)	5. TYPE OF REPORT & PERIOD COVERED
CRYOGENICALLY-COOLED MICROWAVE ACOUSTIC DELAY DEVICES.	Interim report on a continuing NRL problem.
	6. PERFORMING ORG. REPORT NUMBER

7. AUTHOR(s)	8. CONTRACT OR GRANT NUMBER(s)
R. D. Gurney Richard D. Gurney	

9. PERFORMING ORGANIZATION NAME AND ADDRESS	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
Naval Research Laboratory Washington, D. C. 20375	NRL Problem R06-86

11. CONTROLLING OFFICE NAME AND ADDRESS	12. REPORT DATE
	Jan 1978
	13. NUMBER OF PAGES
	23

14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)	15. SECURITY CLASS. (of this report)
	UNCLASSIFIED
	15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Delay
Microwave acoustic
Cryogenic

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

RF components which provide delay of microwave signals are important elements of deception electronic warfare systems. Acoustic devices are attractive for this application because of their small size and lack of dispersion, but at high frequencies and longer delays the insertion loss is substantial. This report describes work toward the development of cryogenically-cooled sapphire delay devices operating in I/J band (8-20 GHz).

CRYOGENICALLY-COOLED MICROWAVE ACOUSTIC
DELAY DEVICE

INTRODUCTION

RF components which provide delay of microwave signals are widely used in deception electronic countermeasures systems. Techniques for implementing delay include lengths of coax and waveguide transmission line, and acoustic devices using mercury or quartz and sapphire crystals. The acoustic devices have the advantage of small size (because of the low acoustic velocity), no dispersion, and loss less than that for long lines at high frequencies. A comparison of the relative losses at 10 GHz is shown in Figure 1. Because of the basic superiority of the crystal delay lines for microwave system use, designers have been trying to further reduce their loss to allow less stringent requirements on associated components such as solid state amplifiers and TWT's. This report describes work toward the development of cryogenically-cooled sapphire delay lines operating in I/J band (8-20 GHz).

SYSTEM CONSTRAINTS

Electronic warfare systems can only tolerate a certain amount of loss in the delay device before the signal-to-noise ratio (s/n) becomes too low for acceptable performance. In many systems the delay device is sandwiched between amplifiers to best maintain signal strength, and by making some assumptions about these amplifiers, we can estimate the maximum allowable insertion loss. The noise level at the input to an amplifier is given by

$$N = (NF) \ kT \ B \tag{1}$$

where NF is the amplifier noise figure, kT the room temperature noise power (-114 dB/MHz), and B the bandwidth.

Note: Manuscript submitted January 3, 1978.

A typical noise figure for a broadband high gain 1 watt TWT
is 25 dB. Let the bandwidth be 8 GHz or 39 dB above 1 MHz.
Then the equivalent input noise power becomes

$$N = 25 - 114 + 39 = -50 \text{ dBm} \qquad (2)$$

Assuming a minimum s/n of 10 dB then requires that the
input signal must not fall below -40 dBm to be useful in
the system. If the maximum signal level into the
delay device is 1 watt (+30 dBm), which is a typical
transducer power limit, the maximum allowable delay loss
is 70 dB. These results will vary slightly with the exact
system, but the above are reasonable assumptions by which
to set delay line design goals.

ACOUSTIC DELAY FUNDAMENTALS

The chief task in achieving a low loss delay line lies
in designing an efficient transducer to convert the input
RF signal to and from an acoustic one. A significant
portion of the total loss is associated with this double
transduction process. We know that if an oscillating
electric field is placed across a properly cut piezo-
electric crystal, the crystal will vibrate at the same
frequency. Quartz is widely used in this manner as a
resonator. Since for best coupling efficiency the crystal
thickness should approximate half an acoustic wavelength,
at microwave frequencies the desired thickness is less than
0.5 micron (5000 Å). At lower frequencies (below 0.5-
1.0 GHz) a crystal platelet can be mechanically and
chemically polished to achieve the proper thickness, but
for the thin layers needed at high frequencies this becomes
extremely difficult. Most workers have used various vacuum
deposition techniques to create a crystalline layer of the
piezoelectric material directly on the end surface of the
delay rod. The basic structure of a bulk acoustic delay
device is shown in Figure 2.

Sapphire is the most widely used delay crystal because
it is readily available in good quality and because its
attenuation for longitudinal waves is the lowest of known
materials. Researchers have determined that lower
attenuation is possible for a few other crystals if shear
propagation is permitted. The generation of this mode is

difficult, however, using thin films because it is hard to
grow transducer films with the proper crystal orientation
thin enough for microwave use.[+]

Early transducer work used cadmium sulfide as the
piezoelectric material, but most recent projects have
concentrated on zinc oxide (ZnO), which is somewhat easier
to grow and which has higher conversion efficiency[3].
Zinc oxide is deposited onto the delay crystal rod by
sputtering it from a disc of compressed ZnO. With thin
layers a true single crystal does not result; generally the
c-axis grows perpendicularly to the substrate, with the
other axes at random orientations. Since for longitudinal
waves the degree of coupling depends only on the c-axis
positioning, this crystalline structure is sufficient.
The longitudinal wave coupling coefficient, k, which is a
measure of the electromechanical energy conversion, is
0.28 for bulk ZnO, but deposited thin films rarely reach this
value[4]. Improper growth conditions or the presence of
impurities apparently cause the c-axis to tilt from
perpendicular or become random; this lowers the effective
k value.

Metal electrodes are required on each side of the
piezoelectric layer to apply the external electric field.
It is important that these films be thin (~ 1000 Å) and
of the proper materials so as to incur the minimum acoustic
signal loss. Furthermore, any acoustic mismatch
significantly affects the transducer frequency response.
Silver has the closest acoustic impedance to sapphire and
is a good match to zinc oxide as well, but because of
silver's oxidation tendency gold is generally used instead.
A very thin (100-200 Å) layer of chromium or titanium
serves to improve the adhesion between the gold film and
the crystal face.

[+]It should be noted that RCA[1,2] has done promising work
using magnesium aluminate spinel in the shear mode as the
delay crystal and properly oriented single crystal plate-
lets of lithium niobate as the transducer. The platelets
were thinned down with ion beam milling to the desired
thickness after being bonded with gold to the crystal.

TRANSDUCER ELECTRICAL BEHAVIOR

The transducer may be modeled by an equivalent electrical circuit as shown in Figure 3. This circuit differs from the usual one[5] by the presence of a variable acoustic load, R_T, across the top electrode. The behavior of this circuit was analyzed in a computer program (described in a separate report[6]) similar to that of other researchers[5]. Materials and layer thicknesses could be varied, and the program would compute and plot the frequency response. The main results are summarized here.

If one first assumes that the metal layers are extremely thin, so that they may be ignored, then the input impedance at terminal 1-1 is given by

$$Z_{in} = 1/j\omega C_o + Z_a \qquad (3)$$

where C_o is the layer capacitance, ω the angular frequency, and Z_a a complex acoustic radiation impedance. These terms are defined by

$$C_o = \frac{\epsilon A}{t} \qquad (4)$$

$$\omega = 2\pi f \qquad (5)$$

$$Z_a = R_a + jX_a \qquad (6)$$

where A is the active transducer area, t its thickness, ϵ the dielectric permittivity, and f the frequency. At the half-wavelength resonant frequency, ω_o, of the piezo-electric layer

$$R_a = (4k^2 R_D/\pi Z_o)(1/\omega_o C_o).$$

From this form we see that the coupling coefficient directly affects the transducer performance; for every halving of its value the conversion loss for each transduction rises by 6 dB, or 12 dB for the entire process. The transducer is capacitive and presents a severe mismatch to the 50 ohm system, reflecting a considerable part of the input power.

4

The exact computer analysis shows that having a finitely-thick bottom electrode adds 2-4 dB of ripple in the passband. If no top electrode acoustic loading is assumed, the thickness of that electrode is crucial to the passband shape because destructive interference from the surface reflections can introduce large loss poles[7]. In cases in which the top electrode can be intimately attached to an acoustic absorber, as when a gold wire is tightly bonded to it for electrical connection, most of the stray energy will be absorbed and not seriously affect the frequency response (the overall loss is increased 2-3 dB for each transducer, though, as might be expected[8].)

The other contributions to the overall delay device loss come from diffraction, attenuation in the bottom electrode mode, and attenuation in the crystalline delay material. For the small diameter top electrodes that are desirable for best electrical match, the acoustic beam will spread out enough that the receiving transducer will not pick up all the available energy. Given the electrode size, crystal length, and frequency, the loss due to diffraction can be estimated. Typically this might vary from about 6-8 dB near 6 GHz to 2-3 dB at 12-15 GHz. Loss in the thin bottom electrode material is fairly negligible for longitudinal propagation because the attenuation in gold is only about 2 dB/micron at 10 GHz. The major loss contribution comes from scattering-induced attenuation in the delay crystal. The loss even for sapphire is about 22-26 dB/μsec at 10 GHz. Furthermore, the attenuation increases in proportion to the square of the frequency: at 15 GHz the loss would be about 54 dB/μsec. The main contributions to the total loss of the 0.75 μsec delay device discussed later in this report are shown in Figure 4.

The material attenuation can be controlled in two ways. For many applications a short delay (0.125-0.25 μsec) is sufficient, which keeps the loss, even in J band, on the order of 10-14 dB. When possible this is the preferred approach. For those cases where longer amounts of delay are imperative, however, operation of the delay device at cryogenic temperatures (60-80°K) will significantly reduce the attenuation. This is because temperature-dependent vibration in the crystal is much reduced resulting in a lessening of the acoustic signal phonons' scatter. By cooling to below 50°K the loss in sapphire at 8 GHz is

lowered from about 13 dB/μsec to less than 1 dB/μsec.

TRANSDUCER FABRICATION

The ZnO transducers for the test delay devices were deposited on freshly evaporated chromium/gold bottom electrodes in a DC sputtering vacuum system. By placing a large voltage (2-3 KV) across the electrode plates holding the sample crystal and the zinc oxide disc, the argon-oxygen gas introduced into the system is ionized. The charged particles accelerate toward the disc, physically knocking ZnO atoms from it onto the crystal face. With a bias of 3 KV across a 2.5 cm gap and an argon-oxygen (80-20) pressure of 6.67 Pa (50 microns), a film approximately 0.4 microns thick could be deposited in less than 15 minutes. During a run the target was cooled with running water and an auxiliary liquid nitrogen cold trap kept the atmosphere as clean as possible. The initial power level under these conditions was slightly over 100 watts, but as the target was bombarded this rapidly dropped to about 30 watts where it remained stable.

Film thickness could be estimated from the color of the film and the sputtering time. A more precise method was to etch away a portion of the film with phosphoric acid, and then examine the interface under an interference microscope. At the thickness step the interference fringes shift in proportion to the thickness and it is possible to fairly accurately determine the thickness. With the 7.5 cm diameter target used, the thickness uniformity across the 0.6 cm diameter crystal face was acceptable but not good (~30% variation). This variation made it impractical to use a quartz monitor to control the thickness. Growing good, repeatable transducer films was the most difficult aspect of this experiment, since slight variations in deposition conditions or impurities in the vacuum system can cause inactive layers or poor crystal structure to form.

EXPERIMENTAL CONDITIONS

To measure the attenuation reduction as a function of temperature a delay crystal was mounted in a waveguide holder at the bottom of a variable temperatue liquid helium dewar (the temperature controlled by heating

6

evaporated helium gas.) The insertion loss was measured by RF substitution in a very sensitive superheterodyne receiving system. Because of the extreme temperature variation (leading to metal holder contraction) and the length of a test, the material loss was determined by subtracting the measured loss of successive echos from each other. This procedure removed all common errors in the data. Figures 5 and 6 show oscilloscope targets of the echo patterns of a 0.55 μsec delay crystal at 70°K and 225°K respectively. Because of the low material loss at 70°K many more echoes are visible. (In fact, in some cases where good triple-travel echo supression is required, such low loss would be a hindrance.) Figure 7 displays the measured loss versus temperature of sapphire at 8 GHz. For this figure the loss at 4°K is set equal to zero; the actual residual loss, depending on crystalline defects, typically is less than 2 dB but is hard to accurately measure. The curve graphically portrays the improvements possible with the cooled line.

Clearly such a dewar cannot be included as part of a practical piece of equipment for field use because it is bulky and fragile, as well as requiring a source of liquid helium. Fortunately, relatively small closed-cycle mechanical refrigerators are available which can reach 60°K or lower, requiring only electricity (about 600 watts) to operate. We chose the laboratory version of a militarized infrared detector refrigerator, the model CS-1003, made by Air Products and Chemicals, Inc. The two versions differ only in the compressor; for economy the lab type uses a large modified air conditioning compressor while the other has a small high speed dry lubricant compressor. The military version weighs about 7.26 kg (16 pounds), occupies less than 71 cu. cm (0.25 cu. ft.), and costs $13K in small quantities. The cold head fits inside an evacuated stainless steel can for thermal insulation while an inner shield made from layers of aluminized plastic film superinsulation further reduces heat loss. Temperature is monitored with a Fe/Au-Chromel thermocouple and an electrical resistance heater provides fine temperature control. The RF signal is carried by a miniature stainless coax cable, which has low thermal conduction. The various refrigerator parts, minus the compressor, are shown in the photograph in Figure 8.

RESULTS

The transducers were first tested in a waveguide holder in which a particular frequency could be tuned by

adjusting a sliding short circuit. A short probe coupled
the energy from the waveguide to the delay crystal, with
electrical contact made with a miniature bellows
(Servometer Corp. type SK-4125). However, in order to
compare transducer behavior to the theoretical model untuned
response must be measured. A 50 ohm coaxial holder mounted
on a small three-axis positioner was made for this purpose.
Because it was untuned the overall loss increased
somewhat over that measured with the waveguide holder.
A simple holder using a short length of 50 ohm microstrip
transmission line wirebonded to the transducer electrodes
was the final configuration tested, this one primarily
for use in the cryogenic refrigerator. A photograph of this
holder is shown in Figure 9. Some difficulty was found
in bonding to the small top electrode because the dot
was hard to see and because the bonding pressure some-
times damaged the ZnO.

One of the delay lines (.75 μsec) was measured at room
temperature with all three holders. All measurements
were taken by RF substitution using calibrated attenuators
and a sensitive heterodyne receiver arrangement.
Figure 10 shows the measured response along with a
theoretical curve adjusted to fit the coaxial probe data
points. The thickness and area values were estimated
from the evaporation parameters while the coupling
coefficient and, to a lesser extent, the material
attenuation were varied to yield a decent fit. The value
for sapphire attenuation was increased from the normal
22 dB/μsec (10 GHz) to 27 dB/μsec to better follow the
data. More importantly, the coupling coefficient had to
be lowered to 0.11 from the bulk value of 0.28. While it
is virtually impossible to obtain the bulk value with a
thin film, other researchers have been able to reach as
much as 0.25 with good films[9] and Larson and Finnley of
the Electronics Division of NRL have obtained 0.16[10].
If a higher degree of coupling had been possible the
insertion loss would have been reduced by about 14 dB.
Improvements, particularly at the high frequency end, of
a few dB would have resulted from a smaller diameter top
electrode and slightly thinner ZnO layer.

This same delay crystal, in the microstrip mount,
was measured at cryogenic temperature in the mechanical
refrigerator. The averaged results from three separate

8

runs at about 65°K are shown in Figure 11. A
substantial reduction in loss is observed although the
slope would indicate that there remains some residual
material attenuation. The reduction would have been more
impressive with an excellent transducer; the final loss
then would have been about 50 dB at 10 GHz. This amount
of loss could easily be recovered with a solid state
amplifier or TWT, leaving a good signal-to-noise ratio at
a useable power level.

The theoretical curves of Figure 12 suggest the
magnitude of improvement that could be expected by using
cryogenic cooling to achieve low crystal attenuation.
Two ZnO/sapphire delay lines are shown, 1.0 and 0.25 μsec
in length, with a fairly good coupling coefficient of 0.22,
both at normal and cryogenically-reduced values of
attenuation. A residual loss of 3 dB/μsec at 10 GHz is
used as suitable for 60-70°K operation. The cryogenic
case has both lower and flatter frequency response.
The 1.0 μsec device remains near or below 60 dB even up
to 16 GHz, which is extremely good.

CONCLUSIONS

Noise considerations in ECM system restrict the
insertion loss of delay devices to approximately 70 dB.
The room temperature loss of microwave bulk acoustic delay
devices, which because of their size are desirable for such
systems, is above this limit for delays in excess of about
0.5 μsec in J band, even with high quality transducer films.
This program has demonstrated that improved loss is
achievable at temperatures which a relatively small
mechanical refrigerator can provide. With the loss
reduced to the 50-60 dB range it is likely that solid state
(FET) amplifiers or medium gain TWT's can then be used in
the circuit.

ACKNOWLEDGEMENTS

The author is grateful to Dr. G. Friedman and A. Elia
for assistance with the circuit analysis, Dr. E.
Alexander for suggestions concerning the transducer
deposition, and Dick Prom, Code 2358, for performing the
wirebonding.

REFERENCES

1. Huang, H.C. et al, "Fabrication of submicron LiNbO$_3$ transducers for microwave acoustic (bulk) delay lines", Appl. Phys. Lett., 24, p. 109, 1974

2. Huang, H.C., "Ultra wide bandwidth, low loss bulk acoustic delay line", IEDM Tech. Digest, p. 156, 1974

3. Foster, N.F., "The deposition, structure and performance of thin film piezoelectric transducers", Proceedings 1968 Sendai Symposium on Acoustoelectronics, p. 11, 1968

4. Larson, J.D. et al, "RF diode sputtered ZnO transducers", IEEE Trans. Sonics & Ultrasonics, SU-18, p. 18, 1972

5. Reeder, T.M. and D.K. Winslow, "Characteristics of microwave acoustic transducers for volume wave excitation", IEEE Trans. Micr. Theory & Tech., MTT-17, p. 927, 1969

6. Gurney, R.D., Microwave Acoustic Bulk-Wave Transducer Analysis, NRL Memorandum Report 3621, in preparation

7. Larson, J.D. et al, "Effect of top electrode thickness on the performance of microwave acoustic transducers", IEEE Trans. Micr. Theory & Tech., MTT-18, p. 602, 1970

8. Kaul, R. et al, "Multi-piezo film microwave acoustic transducers", 1974 MTT Symposium Proceedings, p. 250, 1974

9. Denburg, D.L., "Wide-bandwidth high-coupling sputtered ZnO transducers on sapphire", IEEE Trans. Sonics & Ultrasonics, SU-18, p. 31, 1971

10. Larson, T.R. and M. Finnley, Properties of RF Sputtered Zinc Oxide Thin Films for Microwave Acoustic Devices, NRL Report 7737, 1974
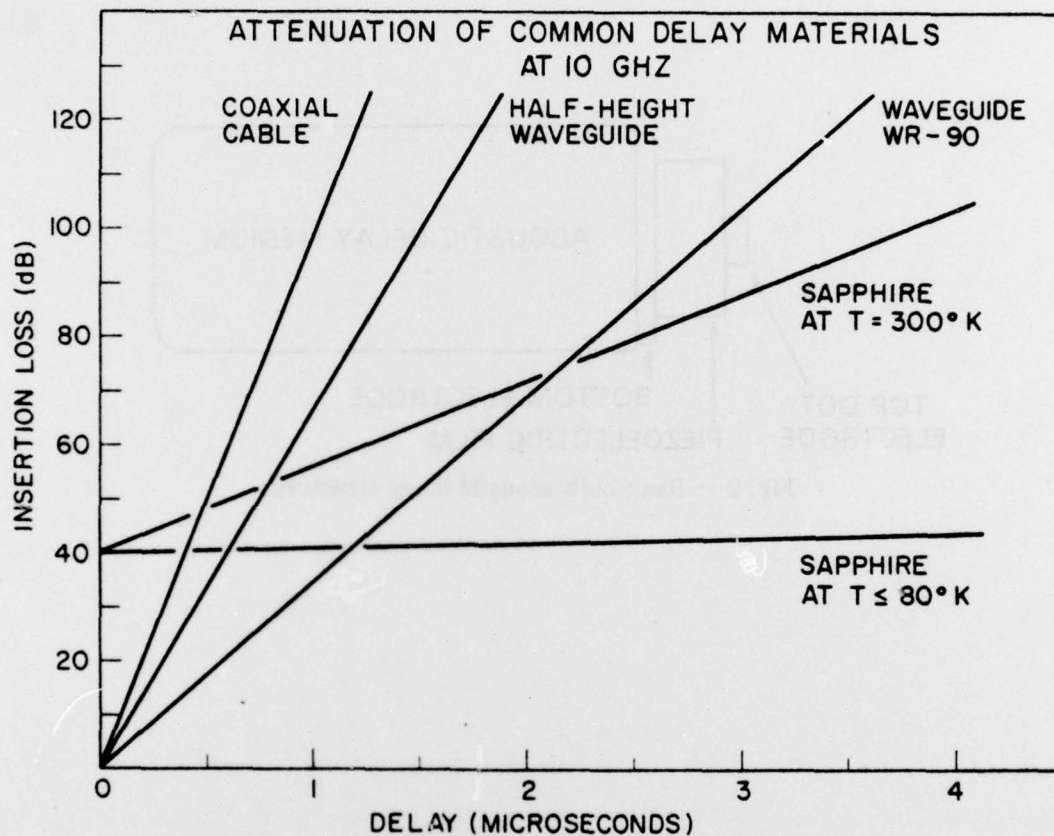
Fig. 1 — Comparison of approximate loss versus delay of different delay approaches at 10 GHz
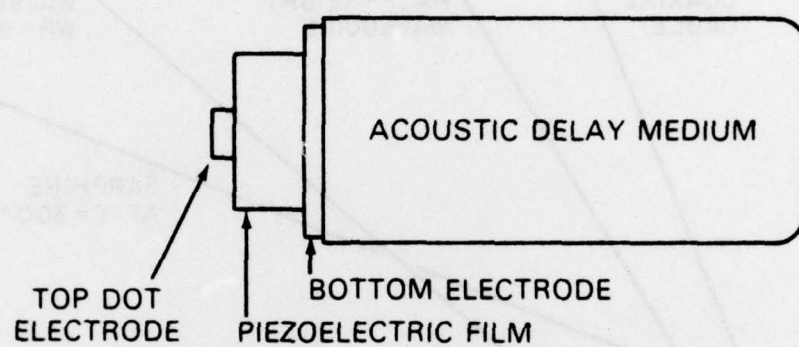
Fig. 2 — Basic bulk acoustic delay structure
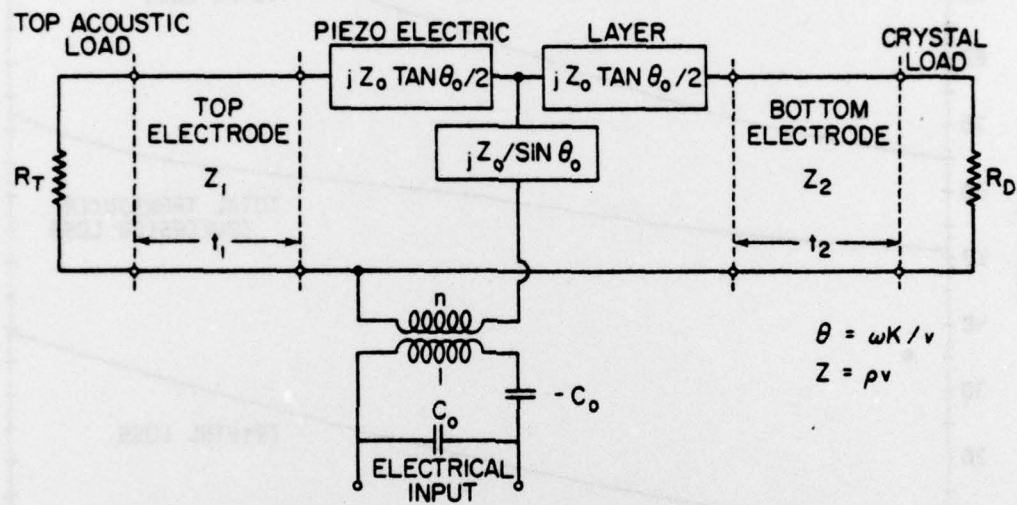
TRANSDUCER MODEL

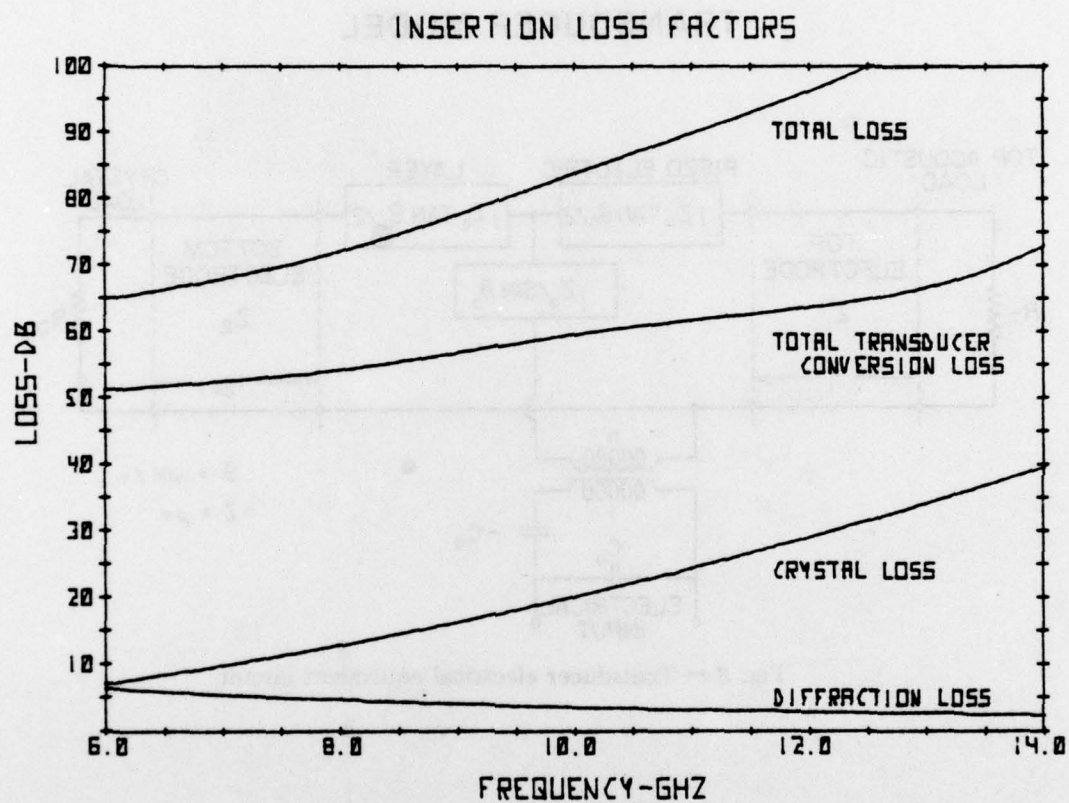Fig. 3 — Transducer electrical equivalent circuit

INSERTION LOSS FACTORS

Fig. 4 — Insertion loss versus frequency along with sources of loss for 0.75 μsec delay line described in text and Fig. 9

14

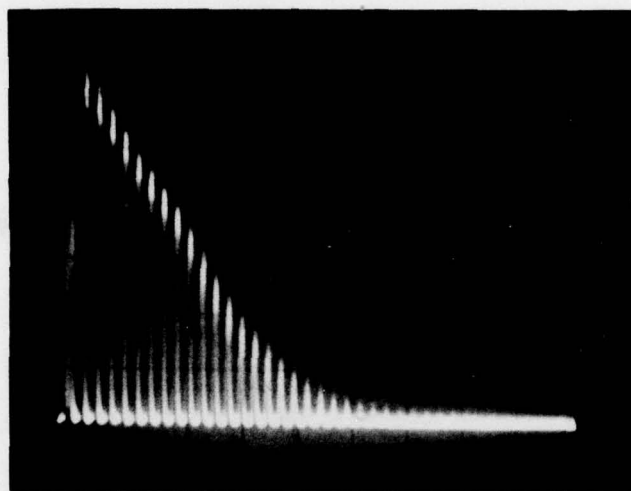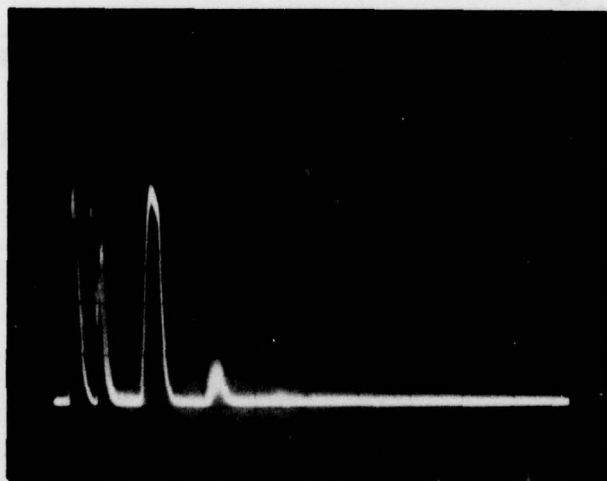Fig. 5 — Multiple acoustic echos of 0.55 μsec delay crystal at 70 °K. Vert.: 0.05 V/div. Horz.: 5 μsec/div.

Fig. 6 — Acoustic echos of same delay crystal at 225 °K. First ragged peak due to transmitter leakage. Vert.: 0.05 V/div. Horz.: 1 μsec/div.
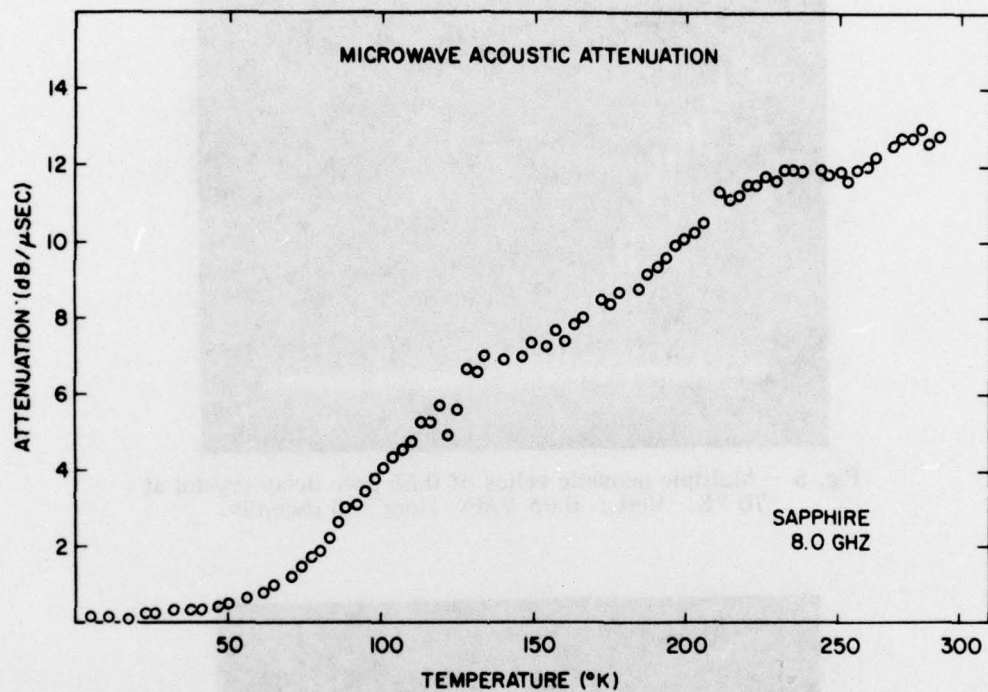
Fig. 7 — Measured attenuation versus temperature of sapphire
at 8.0 GHz
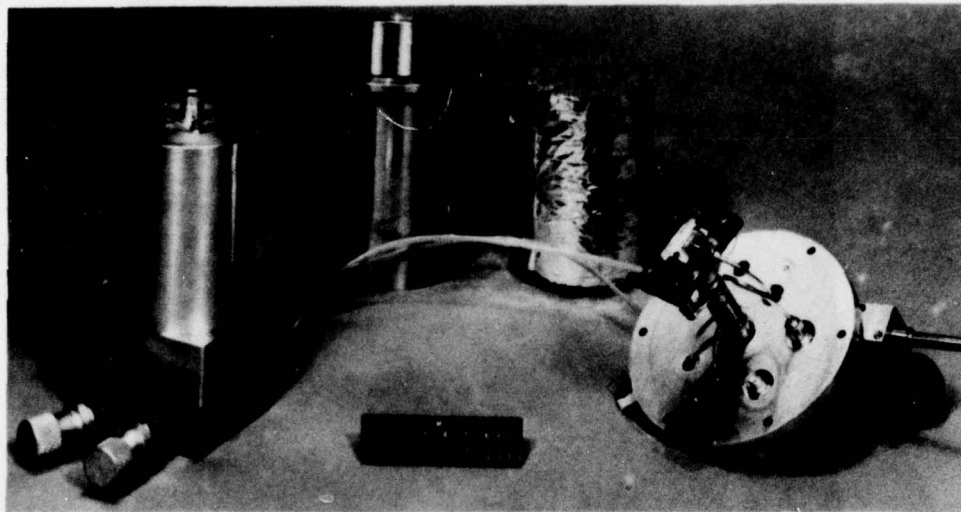
Fig. 8 — Mechanical refrigerator parts, minus compressor, showing cold head with mounted delay device, evacuation can, and superinsulation shielding
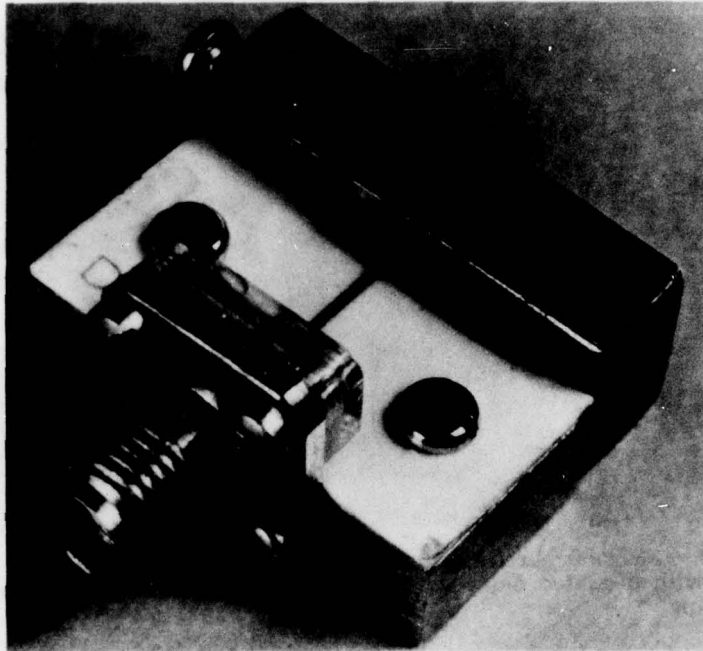
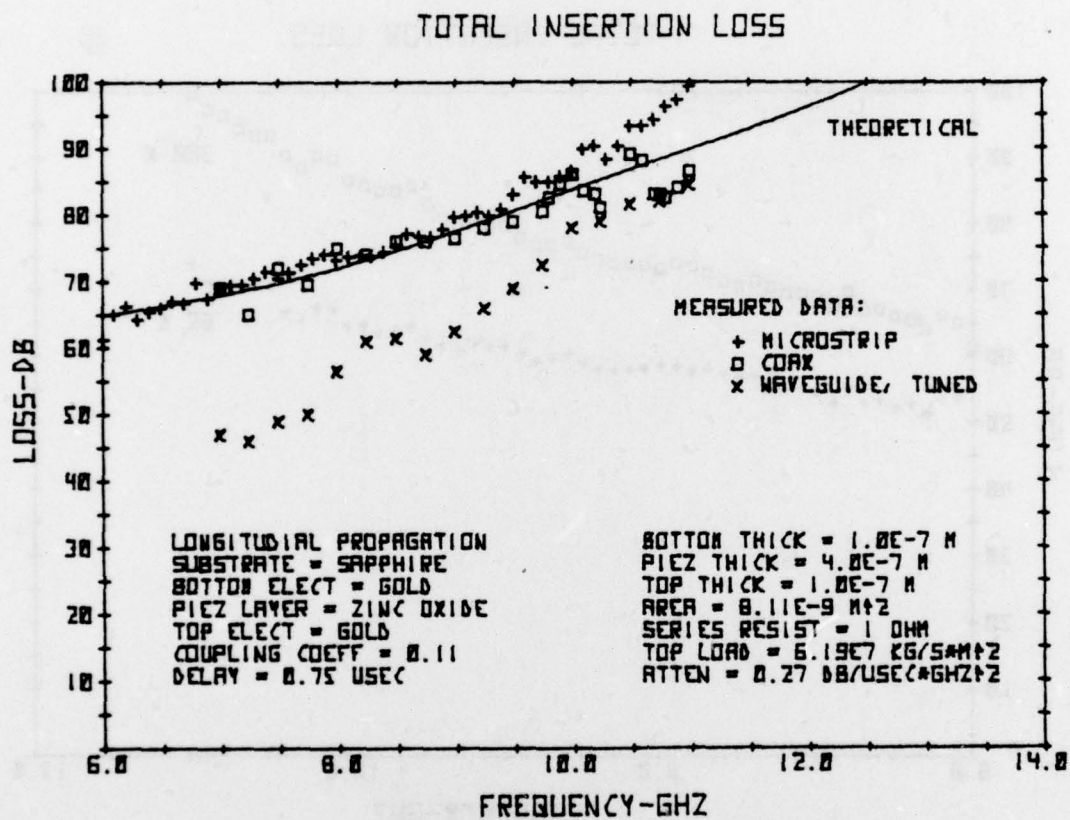Fig. 9 — Microstrip holder with sapphire crystal bonded in place

TOTAL INSERTION LOSS

Fig. 10 — Measured insertion loss versus frequency of 0.75 μsec delay device along with theoretical curve. The computer program input values are listed.
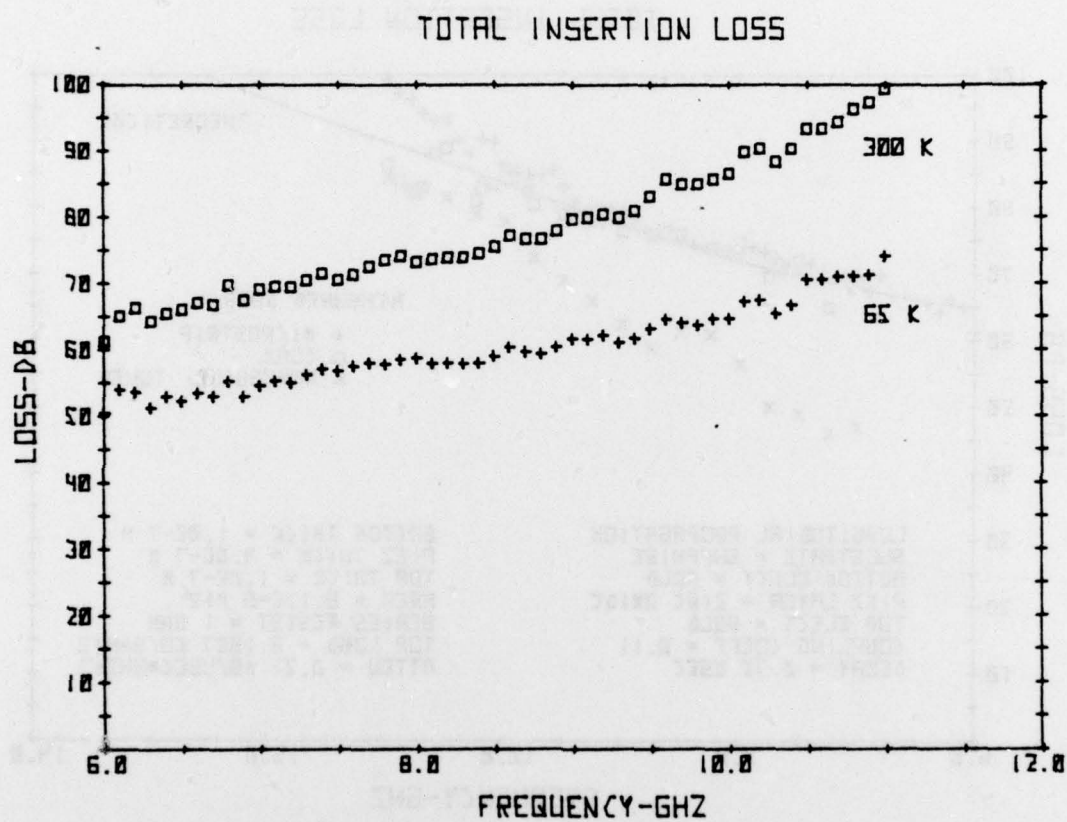
TOTAL INSERTION LOSS

Fig. 11 — Measured insertion loss versus frequency of the same delay device in microstrip mount at 65 and 300 °K
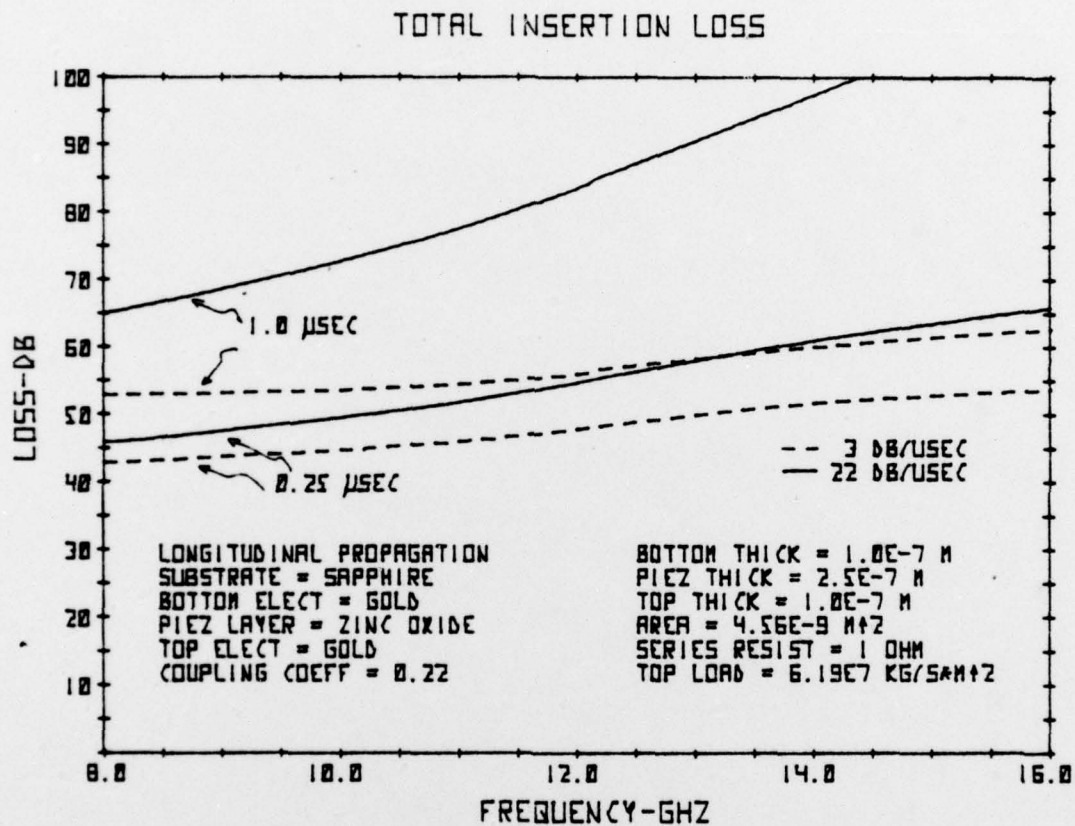
TOTAL INSERTION LOSS

Fig. 12 — Theoretical insertion loss versus frequency of 1.0 and 0.25
μsec devices at low temperature and room temperature